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Is the Environmental Kuznets Curve Driven by Structural Change? What Extended Time Series May Imply for Developing Countries

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Introduction

Until recently, it was thought that the relationship between economic growth and environmental degradation was a monotonic one, even though there was little agreement as to whether economic growth led to environmental degradation or to increasing environmental quality. At the one extreme there are those who argue that economic growth results in ever increasing use of energy and materials and expanding worker productivity and hence more environmental degeneration. At the other extreme are those who claim that the fastest road to environmental improvement is along the path of economic growth; with higher income comes increased demand for improved environmental protection measures. From this perspective, as Beckerman (1992) put it: "the surest way to improve your environment is to get rich" (quoted by Rothman 1998, pp. 178).

A number of empirical studies in the early 1990s (Grossman and Krueger 1991, 1994; Shafik and Bandyopadhyay 1992; and Panayotou 1992, 1993, and 1995) found a nonmonotonic, inverted U-relationship between a number of local pollutants such as particulates and sulfur dioxide and income suggesting a changing relationship between environment and growth along the course of economic development (see Figure 1). At an early stage of development the environment deteriorates with economic growth until a certain level of per capita income is reached beyond which further increases in income result in environmental improvements. The changing income-environment relationship in the course of economic development, known as the Environmental Kuznets Curve (EKC) was attributed largely to behavioral factors: as income rises the effective demand for environmental quality (an income-elastic amenity) rises and eventually overwhelms any scale effects of economic growth on pollution.

Figure 1: The Environmental Kuznets curve

Environmental
Degradation

Income

5
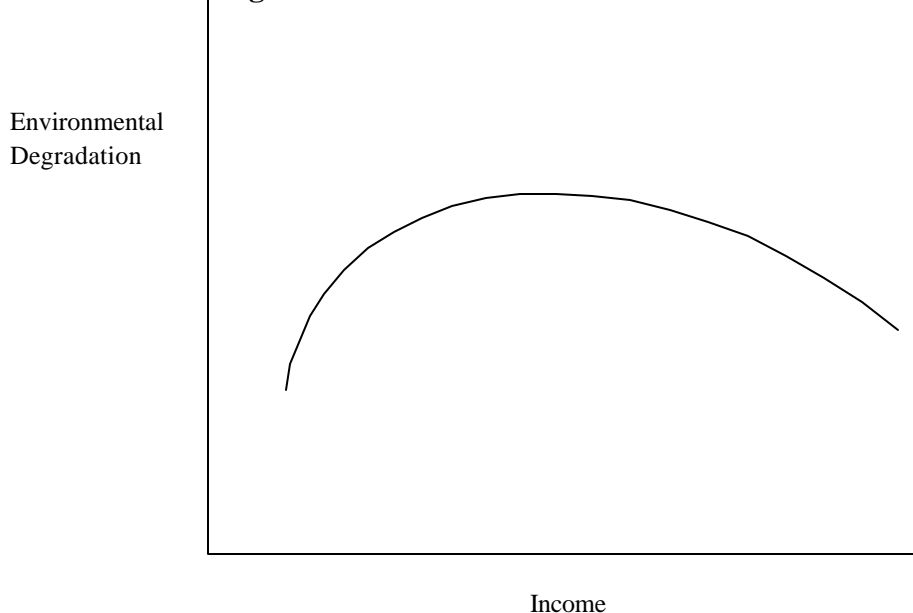
The behavioral explanation of the EKC presumes a perceived impact of pollution on health, quality of life, or welfare more generally; it is the changing valuation of these impacts as income increases that brings about the reversal of the growth-environment relationship. It is, therefore, surprising that empirical studies in the late 1990s (e.g. Schmalensee, Stoker, and Judson 1998 and Panayotou, Sachs, and Peterson 1999) found the same inverted U-relationship between a global pollutant, CO_2, and economic growth. CO_2 is greenhouse gas, which is not visible or in anyway perceptible, and any impact (global warming) it may have is distant, dispersed, and highly uncertain. It is, therefore, unlikely that behavioral changes (due to perceptible climate change) can explain falling CO_2 emissions per capita once a certain level of per capita income is reached. A different explanation is called for.

The Structural Change Hypothesis

The structural change hypothesis proposes that economic growth brings about structural change that shifts the center of gravity of the economy from low-polluting agriculture to high-polluting industry and eventually back to low polluting services. At low levels of development, both the quantity and the intensity of environmental degradation are limited to the impacts of subsistence economic activity on the resource base and limited quantities of biodegradable wastes. As agriculture and resource extraction intensity increase and industrialization takes off, resource depletion and waste generation accelerate. At higher levels of development, structural change towards information-based industries and services can result in a decline in environmental degradation.

Efforts to test this hypothesis using cross-section data have been criticized as misleading (e.g. Stern 1996, Vincent 1997, Unruh and Moomaw 1998). An EKC obtained from cross-country regressions "may simply reflect the juxtaposition of a positive relationship between pollution and income in developing countries with a fundamentally different negative one in developed countries, rather than a single relationship that applies to both categories of countries" (Vincent 1997, pp. 417). This criticism may be valid even for results obtained from panel data (such as Schmalesee, Stoker, and Judson 1998 and Panayotou, Sachs, and Peterson 1999) because of a lack of overlap between developed and developing country data series: all high income observations are from developed countries; all low-income observations are from developing countries (Vincent, 1997).

To address this problem, we test the hypothesis that structural change drives the environmental transition, by using a unique income and population data series that covers the entire period from 1870 to 1994, developed by Maddison (1995b), and CO_2 emissions that date back to 1751 developed by Marland et al (1996). Data for both income and emissions during the period are available for seventeen OECD countries including United Kingdom, the United States, and Japan – three countries that have undergone structural change and environmental transition at different times. This enables us to draw parallel conclusions about present-day developing countries. Doing so, however, is also controversial. An alternative explanation for the downward-sloping segment of the inverted U-shaped relationship, consistent with the structural change hypothesis, is that as countries get richer they spin-off pollution-intensive products to developing countries with lower environmental standards, either through trade or direct investment in these countries. If this is true, the past is not a good predictor of the future; developing counties, as Grossman and Krueger (1995) noted, "will not always be able to find still poorer countries to serve as havens for the production of pollution-intensive goods" (pp. 32). In order to address these concerns, we also test the role of international trade in explaining the environmental transition of present-day developed countries toward lower CO_2 intensities, compared to earlier stages of their development.

A Unique Data Set 1870-1994

We use a unique data set with information on income, population, capital stock, and emissions for the period 1870-1994. This data set covers seventeen advanced countries for all variables except capital stock for which we have information on only six industrialized countries.[1] The sources of this data, and summary statistics are discussed below.

Summary statistics that suggest that the basic income-pollution relationship changes over time are presented in Tables 1, 2, and 3. These tables suggest that emissions increase more rapidly than incomes at early stages of growth, and less rapidly than income as economies become richer. As seen in Table 3, present-day industrial countries were experiencing a more than proportional increase in CO_2 emissions as income increased during 1870-1910, just as do

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[1] The countries for which we have income and emissions data are Australia, Austria, Belgium, Canada, Denmark, Italy, France, Finland, Germany, Japan, Netherlands, New Zealand, Norway, Switzerland, Sweden, United Kingdom, and United States. We have exports data for all these countries except New Zealand. We have capital stock data for France, Germany, Japan, the Netherlands, the U.K., and the U.S.

many developing countries today. The exception is the United Kingdom, which had experienced earlier industrialization, structural change, and environmental transition. From 1910 to 1950, all industrial counties had made the environmental transition to less than proportional growth in emissions except for Japan which was at the same turning point as the U.K. during 1870-1910. From 1950 to 1990, Japan's annual growth rate of emissions fell below that of income while the U.K.'s was reduced to zero despite a 2.2% average growth in income.

The CO_2 emissions data have been calculated by Marland *et al.* (1996), and are published by the Carbon Dioxide Information Analysis Center (CDIAC). CDIAC has estimated global CO_2 emissions from fossil fuel use on a country-by-country basis beginning in 1751. This data is summarized from 1870 to 1990 in Figure 2 and Table 4 for the seventeen countries in our analysis.

As a means of placing these emissions flows in a global context, CDIAC reports that non-OPEC high-income countries contributed 46 percent of combustion emissions in 1996 (not shown in this study). Thirteen percent of total emissions came from Russia and Eastern Europe and 15 percent came from China. The so-called Annex 1 countries (the developed and transition economies that have assumed emissions targets under the Kyoto Protocol) accounted together for 59 percent of emissions. However, these shares are changing rapidly since emissions from Annex 1 countries are leveling off or falling, while emissions from developing countries (non-Annex 1) are growing at 6 to 7 percent per annum.

Before 1960, non-Annex 1 countries, accounting for 77 percent of the world population and only 37 percent of the world income in 1994, were relatively insignificant contributors of CO_2 emissions. While CO_2 emissions from countries like China began rising rapidly at about that time, it was not until 1980 that the share of non-Annex 1 countries in world emissions began to account for one quarter of global emissions from fossil fuels.[2]

The income and population data used in this analysis have been derived by Maddison (1995b). These data are presented in constant Geary-Khamis dollars, a unit that is adjusted to reflect "purchasing-power parity" much like the more familiar Summers and Heston (1992) data set. While Maddison does provide detailed data for a globally representative sample of fifty-six countries, accounting for 93 percent of world output in 1992, we have limited our data set to the

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[2] Details on the distribution of emissions between developed and developing countries are available in Panayotou, Sachs, and Peterson (1999).

developed economies for purposes of isolating the effects of structural transition as discussed previously. Moreover, as discussed below, the variable intended to capture the structural transition from agriculture to industry to services is available for only a limited set of developed countries for the period under consideration.

Table 5 summarizes the increase in income per capita that has been experienced in the developed world since 1870. As Figure 3 makes clear, not only has the increase in absolute levels of income been striking, the developed world also has experienced convergence in incomes over time. This stands in striking contrast to the rest of the world, which has not experienced steady growth in incomes and which has not converged to the level of income of the richest nations. The club of countries under analysis here is the fortunate subgroup for which the 20th century was a profitable one. Figures 4 and 5 contrast the closely bunched scatter plot of income per capita and the dispersed scatter plot of CO_2 emissions per capita. The difference between these images suggests that small differences in incomes can reflect much larger differences in economic structure.

The estimates of gross capital stock have been taken from Maddison (1995a). Time series of capital stock are available for six countries, France, Germany, the Netherlands, Japan, the United States, and the United Kingdom. Complete time series for the period 1870-1992 are available only for the U.K. The total gross physical capital stock is composed of the gross stock of nonresidential structures and the gross stock of machinery and equipment. The capital stock of these six countries is shown on a per capita and per unit of GDP basis in Tables 6 and 7. The year-on-year calculation of capital accumulation is performed using the perpetual inventory method. This means that an estimate is made for each year of new investment of different kinds, and old assets that are scrapped are subtracted. There is additional adjustment using standard assumptions about asset lives and war damage. As Figure 6 shows, the post-World War II period has been marked by a rapid industrialization of Japan and a leveling off in the capital intensity of the U.S. and the U.K. The relationship between this leveling off and emissions of CO_2 is at the heart of this investigation.

Figures 7 and 8 show the pattern of capital accumulation for the U.S. and the U.K. In the U.K. the capital stock grew much more slowly than in the U.S. In both countries, the increase in machinery and equipment over the period of analysis is significantly greater than the increase in nonresidential structures. Technological change has made the machinery and equipment portion

of the capital stock relatively more important as structural change occurs and as the size of the population increased. In this sense, the increasing capital stock reflects both capital "widening" and capital "deepening."

We also investigate the role of trade – both as a cause of emissions itself and as it interacts with the basic income-emissions relationship. We use data from Maddison (1991) on export volumes 1870-1989. This variable is not the ideal measure of trade because it excludes imports, but it should be correlated with the openness of these economies, and thus capture the effect we are interested in. Table 8 shows the trend of exports as a percentage of GDP. The role of exports in income increased significantly following World War II, but was relatively constant before that.

Econometric Estimation

The unique data set that we use for this analysis presents some econometric challenges that have not been a focus of previous EKC research. Previous work (Panayotou, Sachs and Peterson 1999; Schmalensee, Stoker, and Judson 1998; among others) relied upon panel data over 30 to 40 years. In this paper we use 125 years of observations; this means that serial correlation is almost certainly present in our data. That is, high realized values of the dependent variable in any period are likely to be followed by high values of the same variable in the next period. This is common in macroeconomic data. We confirmed this hypothesis by performing Durbin-Watson tests for serial correlation. In almost all cases, the null-hypothesis of no serial correlation is rejected when simple ordinary least squares techniques (OLS) are used. This must be accounted for using feasible generalized least squares (FGLS) techniques in order to get consistent coefficient estimates. Below, we review the econometric specification we use with (1) panel data and (2) time series and explain the statistical treatment of serial correlation in this data.

Panel Data Specification

For the sample of all industrialized countries, we estimate the following reduced-form equation:

(1)

$$e_{it} = \boldsymbol{a}_i + \boldsymbol{b}_1 y_{it} + \boldsymbol{b}_2 y_{it}^{\;2} + \boldsymbol{g} X_{it} + u_i + \boldsymbol{e}_{it}$$

(2) where:

e = ln CO_2 emissions per capita

α = a country specific intercept

y = ln income per capita

X = vector of ln population density, ln exports per unit of GDP, and ln capital per unit of GDP.

u_i = unobserved country-specific, and time invariant, error.

ε_{it} = time variant error, which we assume is produced by an auto-regressive (AR)-1 process.

That is, we assume that:

(3)

$$e_{it} = r_i e_{it-1} + n_{it}$$

where v_{it} is an error term that may be heteroskedastic in structure.[3] Note that this differs from the more common panel data specification in which the error component is assumed to be random, though not necessarily homoskedastic.   We allow for correlation across time periods because we analyze such a long time period and because the macroeconomic variables we consider move relatively slowly from one period to the next.[4]

The assumption of AR-1 correlation provides sufficient structure to this specification that the variance-covariance matrix associated with ε in equation 1 may be estimated if an estimate of ρ_i is available.   Following standard techniques, we estimate ρ_i by (1) estimating equation 1 using

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[3] This error structure makes it clear why OLS does not produce consistent coefficient estimates in the presence of serial correlation. The expectation of ε_t is not zero, but is, in fact, $\rho\varepsilon_{t-1}$.

[4] The Durbin-Watson test is based on the assumption that ε_t and ε_{t-1} have a correlation ρ. The Durbin–Watson

statistic is defined as $d = \dfrac{\sum\limits_{2}^{n} (\hat{e}_t - e_{t-1}) * (\hat{\hat{e}}_t - \hat{e}_{-1})'}{\sum\limits_{2}^{n} \hat{e}_t}$. Durbin and Watson showed that there exists a d_L such that

if $d<d_L$ the null-hypothesis of no autocorrelation should be rejected, and that there exists d_U such that if $d>d_U$ the null-hypothesis of no autocorrelation cannot be rejected. There is also an indeterminate middle range. In Tables 12 and 13 we report the Durbin Watson statistic in the case of OLS and the Durbin Watson statistic in the case of FGLS. The purpose of using FGLS cannot be thought of as a means of getting a Durbin-Watson statistic $d>d_U$ instead of $d<d_L$.

(OLS), (2) using the estimate of ε from this OLS regression to estimate ρ_i in equation 2.[5] This is a consistent estimate if the assumption that the process of AR-1 is correct. With this estimate of ρ_i, equation 1 can be re-estimated using FGLS. As in the usual panel specification, the use of country dummies is sufficient to remove unobserved time-invariant fixed effects from the error term. That is, equation 1 is re-estimated, contingent upon the estimated error structure. If the assumption of AR-1 is a good approximation to the data, these FGLS estimates will be more efficient than OLS, and will be consistent regardless.

Time Series Specification

For the U.S. and the U.K., we estimate equation (1) as a time series specification. A similar technique to the one described above is also used, that is, an estimate of ρ is obtained and then the equation of interest is re-estimated contingent on this value of ρ. As in the case of the panel data, this FGLS technique is an improvement over OLS if the data is close to being AR-1. However, as always, there is the possibility that the error term is correlated with the variables for which we estimate coefficients. Without the freedom offered by panel data to control for unobserved time-invariant elements of the error structure, this is more likely to be true in the case of time series data. In particular, while standard panel data techniques control for the portion of the error that we have designated u_I, there is no way to control for this portion of the error structure in time series analysis.

Empirical Findings

The results of the panel data analysis are reported in Table 9. In model 1 (Regression 1) income per capita and income per capita squared are the only explanatory variables. Both are statistically significant and have the expected sign. Thus, the EKC relationship appears to hold in this panel data set of seventeen industrialized countries over the 124-year period between 1870 and 1994. The implied income elasticity of CO_2 emissions is depicted in Figure 9 as a downward sloping curve between 2.0 and 0.4.

The next models are intended to explore the effects that are driving the EKC in this long time series. We hypothesize that the process of structural change, passing through stages of

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[5] The estimated value of ρ is an indication of how tightly correlated the data series is over time. We provide these estimates in Tables 12 and 13 in the row designated "rho."

development from agriculture, to industry, to services-based economies explains the EKC phenomenon in today's developed countries. To test this, we introduce a variable intended to track capital formation (an industrial economy is more capital-intensive than an agricultural economy, but services-based economies need not have as much capital per unit of GDP as an industrial economy). To understand the effect of structural transformation, we need to control for several effects, in particular changing population density and trade.

Increasing population density has at least two important effects on the structure and emissions intensity of an economy. First, richer economies support more population. In this sense, controlling for population density adds little not already captured by the income variables. Second, and more important for our purposes, increasing population density lowers transportation costs and electric networking costs. As population density in these countries has increased, the resulting lower transport costs may change. This phenomenon could change the emissions structure as distinct from change caused by increasing incomes.

The rationale for controlling for the trading activity of a country is similar to the population density reasoning. On the one hand, increased exports is co-linear with increasing income, and so little additional information is added by introducing an export variable into the reduced form equation. On the other hand, the "pollution-haven" hypothesis suggests that richer countries export their pollution by buying dirty goods from abroad and even produce such goods abroad themselves. This hypothesis, if correct, would suggest that for poor countries, more trade means more pollution, while for rich countries more trade means less pollution; above and beyond simple income effects.

In model 2 we introduce nonresidential capital per unit of GDP as a surrogate for industrialization; it is statistically insignificant. Controlling for population density in model 3 does not alter this result. In model 4 we introduce international trade, represented by the export/GDP ratio; it is statistically significant and positive, suggesting that trade tends to increase rather than reduce CO_2 emissions. In model 5 we add an interaction term between trade and GDP per capita to test the hypothesis that the effect of trade on emissions depends on a country's stage of development. The interaction term is significant but the sign reverses depending on the sample used, being positive for the largest possible sample and negative for there more limited sample for which capital accumulation data are available. Controlling for population density in model 6 does not significantly alter the results. This suggests that, in this sample, the

transportation costs structure effects of increasing population density are less important than the pure income effects. In models 7 and 8 we reintroduce the nonresidential capital stock. In model 8 (where we control for population density) the results suggest that an EKC relationship between CO_2 emissions and trade, with international trade increasing emissions at earlier stages of development and reducing emissions at higher levels. The nonresidential capital stock continues to be insignificant in the complete model, suggesting the possibility that its role might also change as a country develops.[6]

To explore further the apparently changing role of trade and capital stock along a country's development path we divide our panel data into three time periods: 1870-1910, 1910-50, and 1950-90 and we rerun our three basic regression models, equations 2, 5b and 8.

We report the results in Table 10. Here, we discuss only the complete model 8, which includes, in addition to income, trade, capital stock, and population density. The following observations are worth noting:

a) during the period 1910-1950 that encompasses two world wars and the great depression, very little is found to be statistically significant; neither income, nor trade can explain variations in CO_2 emissions; only population density (-) and nonresidential capital stock (+) have any explanatory power;

b) during the preceding period, 1870-1910, trade contributes to emissions but at a decreasing rate as income increases, while both population density and capital stock contribute to higher emissions.

c) It is only in the most recent period, 1950-1990, when both population density and capital stock make negative contributions to emissions, that income is statistically significant and the signs are as expected. Trade still contributes to higher emissions at a decreasing rate as income increases but its contribution is significantly reduced compared to the period 1870-1910.

d) The rise and fall in the contribution of the capital stock per unit of GDP to emissions (its emissions elasticity rises from 0.42 to 0.76 and falls to –0.19) lends support to the structural change hypothesis.

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[6] Of course there are other explanations such as the significantly reduced sample for which capital stock data are available. It may also truly lack explanatory power and should be rejected.

We have also attempted time series analysis for two countries, the U.S. and U.K. (the results are reported in Tables 11 and 12). While the number of observations is drastically reduced and the results should be interpreted with caution, two points may be worth noting: (a) the EKC hypothesis is generally supported for both countries, and (b) the trade elasticity is fairly stable in the U.K. but changing in the U.S. while the reverse is true of the capital stock elasticity: it is stable in the U.S. but unstable in the U.K.

Conclusion and Policy Implications

The purpose of this short paper was to test the robustness of the Environmental Kuznets Curve, an inverted U-shaped relationship between income and CO_2 emissions, using long-time series rather than cross section or "nonoverlapping" panel data, and to explore the role of structural change and trade in the income-environment relationship. For this purpose, we used a unique data set for seventeen OECD countries that spans 124 years; although data for a key variable, nonresidential capital stock, were available for only six countries. The findings of the econometric analysis, while lending support to the EKC over the long haul of 124 years (Figures 10, 11, and 13), are less persuasive when the data is divided into three forty-year periods.

Of particular interest is the changing role of the non-residential capital stock, used to represent structural change, along the development path. In early stages of development, capital accumulation results in rising emissions; its contribution to emissions rises as the country industrializes, but falls and becomes negative in the postindustrial stage. Trade generally increases emissions, but, at high levels of incomes, trade tends to reduce them (see Figures 12 and 14). This appears to be consistent with the "pollution-haven" hypothesis that asserts that the downward sloping part of the EKC is due to the spinning-off of polluting products to developing countries through trade and foreign investment. However, the persistence of the EKC in the presence of statistically significant trade terms in the complete model for the period 1870-1994 and for the 1950-1994 period suggests that trade cannot explain away the EKC for CO_2 emissions even if it contributes to it.

Clearly, further research is needed to untangle the diverse and shifting forces underlying the environment-growth relationship. What is clear is that developing and developed countries find themselves on different sides of the EKC. Developing countries find themselves where the U.K. was 150 years ago, the U.S. 100 years ago, and Japan 50 years ago, when income growth,

structural change, capital accumulation, and trade all contributed to rapidly growing CO_2 emissions. Unless alternative development and energy paths are found that do not constrain their growth prospects, developing countries are unlikely to participate in global efforts to control greenhouse gases and reduce the threat of global warming. Developed country commitments alone would not suffice. Simply waiting for developing country EKCs for CO_2 emissions to turn down is likely to be extremely costly in terms of damages experienced as a result of climate change. The implication is that the developed countries, which are in the forefront of technological innovation, can best meet their own commitments and encourage developing countries to participate by investing heavily in the development of new energy technologies that are clean and that developing countries can afford.

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Table 1: Sample Summary Statistics, 1870-1990

for 17 Industrialized Countries

	1870-1910		1910-1950		1950-1990	
	Average	Standard Dev.	Average	Standard Dev.	Average	Standard Dev.
CO_2 emissions per capita (metric tons of carbon)	0.80	0.83	1.39	1.13	2.40	1.19
Income per capita (1990 G-K $)	2,715	1,046	4,267	1,583	11,357	4,072
Gross nonresidential capital stock per unit of GDP (1990 G-K $)	1.41	0.99	1.59	1.20	1.25	0.96

Source: CDIAC (1997), (emissions); Maddison (1995), (income and population).

Table 2: Cumulative Percent Change of GDP and CO_2 Per Capita 1870 - 1990

for Selected Industrialized Countries

	1870-1910		1910-1950		1950-1990	
	GDP per capita	CO_2 per capita	GDP per capita	CO_2 per capita	GDP per capita	CO_2 per capita
France	58%	178%	78%	32%	241%	29%
Japan	69%	381%	49%	51%	890%	606%
U.K.	44%	44%	45%	-11%	138%	-1%
U.S.	102%	456%	93%	22%	128%	16%
Average Industrial	77%	230%	59%	7%	199%	82%

Source: CDIAC (1997), (emissions); Maddison (1995), (income and population).

Table 3: Average Annual Growth Rates of GDP and CO2 Per Capita 1870 - 1990

for Selected Industrialized Countries

	1870-1910		1910-1950		1950-1990	
	GDP per capita	CO_2 per capita	GDP per capita	CO_2 per capita	GDP per capita	CO_2 per capita
France	1.1%	2.6%	1.4%	0.7%	3.1%	0.6%
Japan	1.3%	18.3%	1.0%	1.0%	5.7%	4.9%
U.K.	0.9%	0.9%	0.9%	-0.3%	2.2%	0.0%
U.S.	1.8%	4.3%	1.6%	0.5%	2.1%	0.4%
Average Industrial	1.4%	3.0%	1.2%	0.2%	2.7%	1.5%

Source: CDIAC (1997), (emissions); Maddison (1995), (income and population).

Table 4: CO$_2$ Emissions Per Capita

for 17 Industrialized Countries (metric tons of carbon)

	1870	1890	1910	1930	1950	1970	1990
Australia	0.10	0.31	1.11	1.13	1.83	3.11	4.26
Austria	0.44	0.66	2.37	0.77	0.82	1.84	2.03
Belgium	1.33	1.78	2.23	3.17	2.41	3.55	2.67
Canada	0.09	0.69	1.96	2.46	3.07	4.19	4.20
Denmark	0.17	0.35	0.72	1.19	1.41	3.43	2.69
Finland	0.01	0.02	0.10	0.21	0.45	2.38	2.80
France	0.36	0.67	1.00	1.63	1.32	2.28	1.70
Germany	0.91	2.04	3.33	3.15	1.79	2.49	3.79
Italy	0.03	0.11	0.19	0.26	0.24	1.45	1.89
Japan	0.00	0.05	0.2212	0.39	0.33	1.94	2.37
Netherlands	0.37	0.62	0.96	1.41	1.38	2.67	2.54
New Zealand		0.58	1.28	0.89	1.23	1.37	1.91
Norway	0.10	0.28	0.68	0.85	0.71	1.76	3.07
Sweden	0.09	0.28	0.65	0.84	1.12	3.13	1.55
Switzerland	0.09	0.27	0.57	0.64	0.60	1.72	1.74
U.K.	2.13	2.75	3.06	2.76	2.71	3.13	2.68
U.S.	0.67	1.73	3.73	3.77	4.55	5.62	5.27
Average	0.43	0.78	1.42	1.50	1.53	2.71	2.77

Source: CDIAC (1997), (emissions); Maddison (1995), (population).

Last entry for Germany is 1991 not 1990.

Table 5: Income Per Capita

for 17 Industrialized Countries (1990 Geary-Khamis Dollars)

	1870	1890	1910	1930	1950	1970	1990
Australia	3,801	4,775	5,581	4,792	7,218	11,637	16,417
Austria	1,875	2,460	3,312	3,610	3,731	9,813	16,792
Belgium	2,641	3,355	3,978	4,873	5,347	10,410	16,807
Canada	1,620	2,254	3,852	4,558	7,057	11,758	19,599
Denmark	1,927	2,428	3,565	5,138	6,683	12,204	17,953
Finland	1,107	1,341	1,851	2,589	4,131	9,302	16,604
France	1,858	2,354	2,937	4,489	5,221	11,558	17,777
Germany	1,913	2,539	3,527	4,049	4,281	11,933	18,685
Italy	1,467	1,631	2,281	2,854	3,425	9,508	15,951
Japan	741	974	1,254	1,780	1,873	9,448	18,548
Netherlands	2,640	3,113	3,684	5,467	5,850	11,671	16,569
New Zealand	3,115	3,774	5,343	4,958	8,495	11,278	13,994
Norway	1,303	1,617	2,052	3,377	4,969	9,122	16,897
Sweden	1,664	2,086	2,980	3,937	6,738	12,717	17,695
Switzerland	2,172		7,068	6,160	8,939	16,671	21,661
U.K.	3,263	4,099	4,715	5,195	6,847	10,694	16,302
U.S.	2,457	3,396	4,970	6,220	9,573	14,854	21,866
Average	2,092	2,637	3,703	4,356	5,905	11,446	17,654

Source: Maddison (1995)

Table 6: Gross Nonresidential Capital Stock Per Capita

for 6 Industrialized Countries (1990 Geary-Khamis Dollars)

	1870	1890	1910	1930	1950	1970	1990
France					8,569	17,331	38,536
Germany					7,818	22,130	44,405
Japan		879	1,458	3,691	5,830	28,582	114,375
Netherlands					12,158	23,098	37,453
U.K.	2,956	3,441	4,213	4,954	5,626	14,079	27,055
USA		10,315	16,397	22,081	23,574	32,429	51,609

Source: Maddison (1995)

Table 7: Gross Nonresidential Capital Stock Per Unit of GDP

for 6 Industrialized Countries (1990 Geary-Khamis Dollars)

	1870	1890	1910	1930	1950	1970	1990
France					0.039	0.029	0.038
Germany					0.036	0.030	0.037
Japan		0.710	0.849	1.318	1.767	1.487	2.789
Netherlands					2.059	1.957	2.231
U.K.	0.902	0.839	0.891	0.939	0.808	1.298	1.642
U.S.		3.037	3.284	3.558	2.436	2.163	2.345

Source: Maddison (1995)

Table 8: Exports Per Unit of GDP (1870-1989)

for 16 Industrialized Countries (1990 Geary-Khamis Dollars)

	1870	1890	1910	1930	1950	1970	1989
Australia	0.07	0.08	0.14	0.12	0.09	0.12	0.14
Austria	0.06			0.06	0.05	0.15	0.29
Belgium	0.09	0.16	0.23	0.17	0.18	0.45	0.75
Canada	0.12	0.09	0.09	0.15	0.13	0.19	0.24
Denmark	0.09	0.11	0.12	0.16	0.13	0.23	0.38
Finland	0.16	0.17	0.22	0.25	0.19	0.31	0.32
France	0.05	0.06	0.08	0.08	0.08	0.13	0.22
Germany	0.15	0.16	0.23	0.20	0.06	0.20	0.36
Italy	0.04	0.04	0.05	0.04	0.04	0.11	0.16
Japan	0.00	0.01	0.02	0.04	0.02	0.07	0.12
Netherlands	0.18	0.16	0.17	0.16	0.13	0.32	0.53
New Zealand							
Norway	0.10	0.12	0.14	0.16	0.14	0.26	0.47
Sweden	0.10	0.12	0.13	0.16	0.16	0.27	0.38
Switzerland	0.19			0.21	0.15	0.31	0.50
U.K.	0.13	0.15	0.18	0.11	0.11	0.13	0.19
U.S.	0.03	0.04	0.03	0.03	0.03	0.04	0.07
Average	0.10	0.11	0.13	0.13	0.11	0.21	0.32

Source: Maddison 1991, Maddison 1995.

Last entry for Germany is 1991 not 1990.

Table 9: FGLS Panel Data Analysis for Industrialized Countries (1870-1994)

Dependent Variable is Ln Emissions Per Capita

	1	2	3	4a	4b	5a	5b	6a	6b	7	8
Ln income per capita	5.38	5.43	5.27	5.78	4.88	6.32	3.68	7.98	3.47	3.69	3.46
	(12.097)	(10.213)	(9.652)	(11.543)	(9.045)	(10.186)	(5.199)	(15.33)	(4.827)	(5.40)	(4.931)
Ln income per capita squared	-0.25	-0.27	-0.25	-0.28	-0.24	-0.31	-0.19	-0.42	-0.18	-0.19	-0.17
	(9.853)	(8.627)	(7.904)	(9.578)	(7.659)	(8.781)	(5.028)	(14.171)	(4.508)	(5.159)	(4.434)
Ln exports per unit GDP				0.12	0.13	-0.22	0.92	-0.32	0.92	0.77	0.08
				(7.855)	(5.463)	(1.22)	(4.089)	(1.97)	(4.104)	(3.380)	(3.527)
Ln exports/GDP * Ln income per capita						0.04	-0.09	0.06	-0.09	-0.08	-0.08
						(1.907)	(3.498)	(1.283)	(3.526)	(2.787)	(2.956)
Ln population density			-0.15					0.59	-0.14		-0.17
			(1.229)					(9.363)	(1.255)		(1.430)
Ln total non-res capital per unit of GDP		0.00	0.00							0.03	0.06
		(0.456)	(0.321)							(0.747)	(1.187)
Constant	-26.52	-25.93	-25.02	-27.66	-22.67	-30.36	-16.09	-82.86	-15.03	-16.59	-15.36
	(13.897)	(11.335)	(10.475)	(12.893)	(9.671)	(11.048)	(4.872)	(1.249)	(4.458)	(5.271)	(4.671)
Number of observations	2071	465	465	1781	453	1781	453	1781	453	453	453
Number of countries	17	6	6	16	6	16	6	16	16	6	6

All estimation performed using country fixed effects.

Estimation performed by FGLS assuming heteroskedasticity and panel-specific AR1 correlation.

Numbers in parentheses are z statistics, rather than the usual t-statistics, but are interpreted in the same manner asymptotically.

Regressions "a" are for largest possible sample, regressions "b" are for subsample for which capital accumulation data is available.

Table 10: FGLS Panel Data Analysis for Industrialized Countries; Preferred Specifications by Time Periods (1870-1994)

Dependent Variable is Ln Emissions Per Capita

	Regression 2			Regression 5b			Regression 8		
	1870-1910	1910-1950	1950-1990	1870-1910	1910-1950	1950-1990	1870-1910	1910-1950	1950-1990
Ln income per capita	16.56	5.09	4.46	-5.39	2.31	4.42	-1.45	0.03	3.09
	(7.086)	(7.109)	(5.261)	(2.233)	(3.071)	(3.987)	(0.686)	(0.031)	(2.752)
Ln income per capita squared	-0.91	-0.26	-0.21	0.28	-0.09	-0.22	0.04	0.09	-0.15
	(6.325)	(5.903)	(4.498)	(2.008)	(1.934)	(3.970)	(.312)	(1.727)	(2.568)
Ln exports per unit GDP				6.44	-0.18	0.68	5.69	0.13	1.15
				(14.067)	(.695)	(1.326)	(13.760)	(0.520)	(2.266)
Ln exports/GDP * Ln income per capital				-0.76	0.04	-0.07	-0.68	0.01	-0.12
				(13.544)	(1.22)	(1.372)	(13.448)	(0.193)	(2.256)
Ln population density							0.44	-1.50	-0.58
							(2.395)	(9.455)	(2.666)
Ln total non-res capital per unit of GDP	1.11	-0.19	0.00				0.42	0.76	-0.19
	(4.962)	(3.863)	(0.266)				(3.704)	(7.983)	(3.256)
Constant	-75.33	-22.66	-21.78	26.61	-11.73	-20.46	8.85	-1.88	-12.42
	(7.901)	(8.025)	(5.689)	(2.544)	(3.603)	(3.689)	(4.671)	(0.513)	(2.100)
Number of observations	79	131	245	79	131	233	79	131	233
Number of countries	3	4	6	3	4	6	3	4	6

All estimation performed using country fixed effects.

Estimation performed by FGLS assuming heteroskedasticity and panel-specific AR1 correlation.

Numbers in parentheses are z statistics, rather than the usual t-statistics, but are interpreted in the same manner asymptotically.

Table 11: Time Series Analysis U.S. (1870-1994)

Dependent Variable is Ln Emissions Per Capita

	All time periods						Regression 1			Regression 6		
	1	2	3	4	5	6	1870-1910	1910-1950	1950-1990	1870-1910	1910-1950	1950-1990
Ln income per capita	8.36	31.27	7.63	7.54	8.75	7.68	8.78	11.47	7.84	2.71	11.36	5.72
	(4.873)	(1.192)	(5.795)	(5.163)	(4.981)	(5.312)	(1.399)	(3.456)	(1.196)	(0.232)	(4.603)	(1.030)
Ln income per capita squared	-0.43	-2.99	-0.39	-0.39	-0.44	-0.39	-0.46	-0.61	-0.39	0.29	-0.67	-0.29
	(4.873)	(1.192)	(5.795)	(4.859)	(4.420)	(4.912)	(1.23)	(3.35)	(1.135)	(0.369)	(5.039)	(1.047)
Ln income per capita cubed		0.10										
		(0.888)										
Ln exports per unit GDP					-0.4606	-0.119				0.72	0.72	-0.06
					(0.613)	(0.185)				(2.437)	(0.474)	(0.968)
Ln exports/GDP * Ln income per capita					0.0522	0.0156				1.71	-0.06	0.02
					(0.635)	(0..222)				(2.408)	(0.381)	(0.906)
Ln population density			0.28									
			(1.653)									
Ln total non-res capital / GDP				-0.02		0.01				-0.97	-0.91	-0.91
				(0.122)		(0.078)				(6.531)	(3.823)	(7.352)
Constant	-39.41	-107.33	-36.33	-35.14	-41.89	35.93	-40.37	-52.14	-38.16	-45.11	-45.11	-25.90
	(5.046)	(1.366)	(6.116)	(6.740)	(5.309)	(5.367)	(1.539)	(3.459)	(1.205)	(0.898)	(5.852)	(0.916)
rho	0.917	0.905	0.931	0.872	0.916	0.871	0.917	0.951	0.790	0.335	0.015	0.862
Durbin Watson statistic	0.222	0.461	0.241	0.360	0.686	0.703	1.015	0.668	0.399	2.389	1.926	0.542
DW statistic (transformed)	*2.543	*2.566	*2.610	*2.483	*2.559	*2.506	*2.572	*2.252	1.641	*2.026	1.908	1.517
Observations	125	125	125	103	120	100	40	39	39	20	39	39
F-statistic	256	387	199	581	177	359	23	280	697	318	3526	1267

Do not reject Ho: rho = 0 at 95% confidence level

All regressions done using Prais-Whinsten FGLS Estimator to correct for first-order auto-correlation

t-statistics calculated using semirobust standard errors in parentheses below coefficient estimates.

Table 12: Time Series Analysis U.K. (1870-1994)

Dependent Variable is Ln Emissions Per Capita

	All time periods						Regression 1			Regression 6		
	1	2	3	4	5	6	1870-1910	1910-1950	1950-1990	1870-'10	'10-'50	'50-'90
Ln income per capita	5.32	23.02	10.26	5.14	4.44	3.20	-0.96	37.30	5.05	7.78	72.19	-10.79
	(8.027)	(0.854)	(3.204)	(6.562)	(3.864)	(2.090)	(-0.057)	(2.148)	(1.646)	(0.999)	(4.717)	(1.315)
Ln income per capita squared	-0.30	-2.29	-0.56	-0.29	-0.30	-0.22	0.10	-2.15	-0.28	-0.56	-4.30	0.44
	(7.94)	(0.758)	(3.292)	(6.431)	(5.343)	(2.835)	(0.104)	(-2.152)	(-1.671)	(1.271)	(4.831)	(1.120)
Ln income per capita cubed		0.07										
		(0.665)										
Ln exports per unit GDP					4.295	4.207				9.903	9.182	13.409
					(3.493)	(3.566)				(3.020)	(6.008)	(2.741)
Ln exports/GDP * Ln income per capita					0.476	-0.464				-1.160	-1.040	-1.472
					(3.427)	(3.495)				(2.973)	(6.035)	(2.772)
Ln population density			-0.778									
			(1.566)									
Ln total non-res capital per unit of GDP				0.002		-0.160				0.43	-0.16	-0.31
				(0.959)		(1.725)				(6.007)	(1.212)	(1.178)
Constant	-22.83	-75.05	-41.98	-22.09	-14.76	-9.62	1.70	-160.95	-22.03	-24.68	-30.10	62.59
	(7.764)	(0.938)	(3.347)	(6.394)	(5.929)	(1.283)	(0.024)	(-2.131)	(-1.546)	(0.713)	(4.577)	(1.490)
rho	0.40	0.40	0.40	0.394	0.317	0.304	0.42	0.21	0.73	0.296	0.292	0.521
Durbin Watson statistic	1.20	1.21	1.21	1.210	1.390	1.413	1.13	0.77	1.62	2.460	1.678	1.030
DW statistic (transformed)	*2.153	*2.158	*2.143	*2.152	*2.073	*2.053	*2.003	1.863	*1.992	*2.120	*2.056	1.742
Observations	125	125	125	121	120	120	40	39	39	40	39	39
F-statistic	5422	85	5036	14181	6778	6200	35	1254	2586	176	1651	3052

Do not reject Ho: rho = 0 at 95% confidence level

All regressions done using Prais-Whinsten FGLS estimator to correct for first-order auto-correlation

t-statistics calculated using semirobust standard errors in parentheses below coefficient estimates.

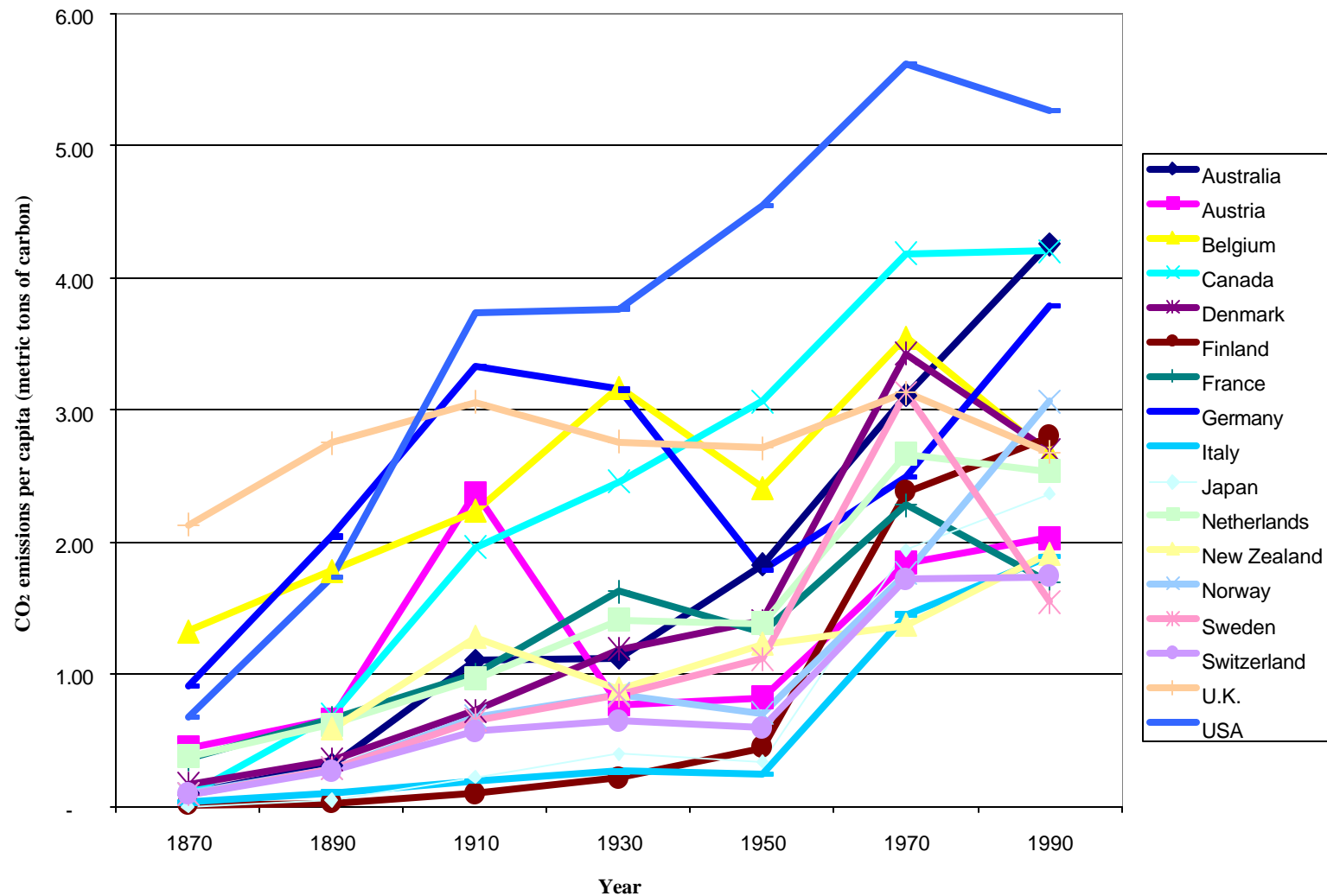**Figure 2: CO2 Emissions Per Capita for 17 Industrialized Countries, 1870-1990 (metric tons of carbon)**

Figure 3: Income Per Capita in 17 Industrialized Countries, 1870-1990 (1990 Geary-Khamis Dollars)
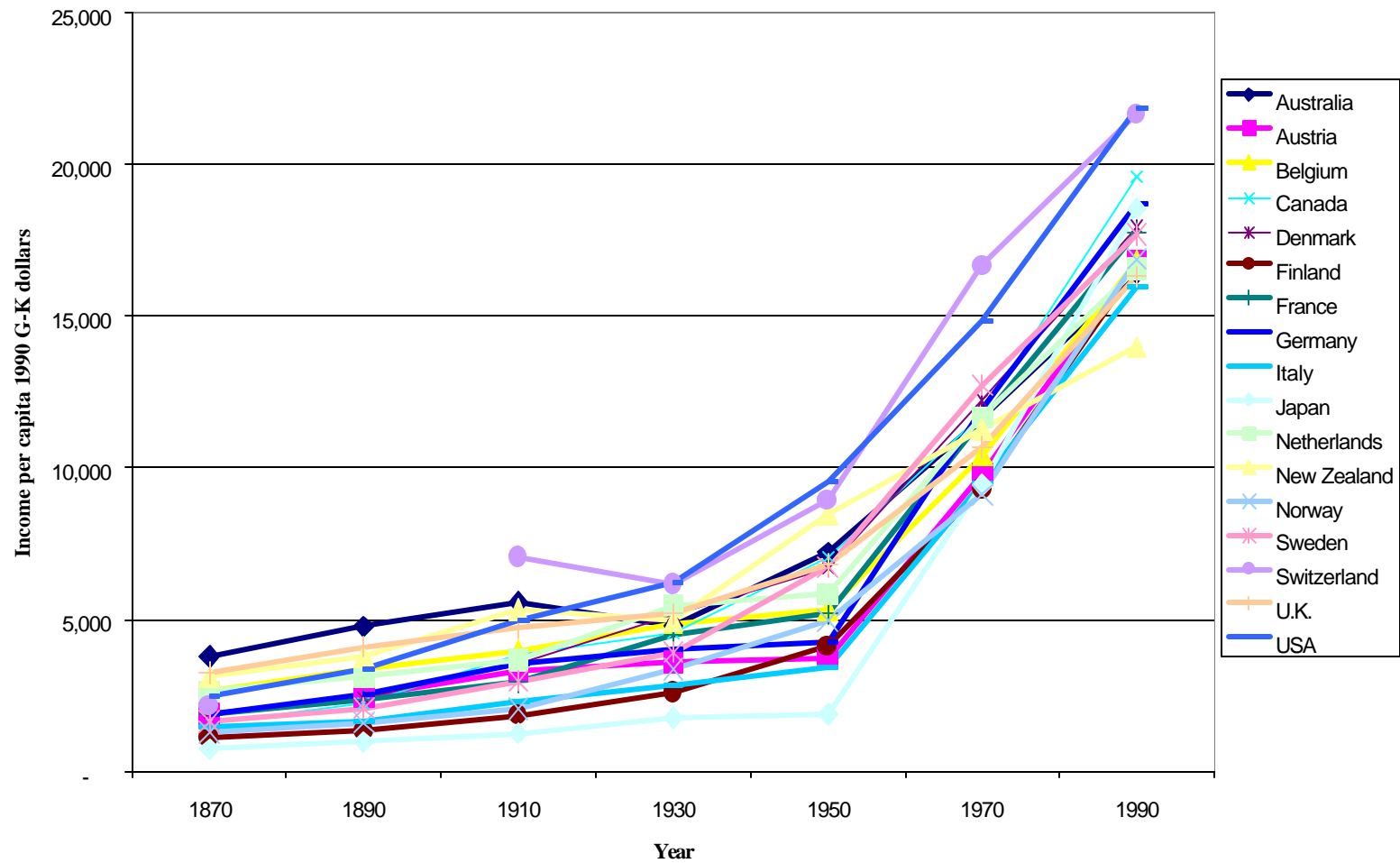
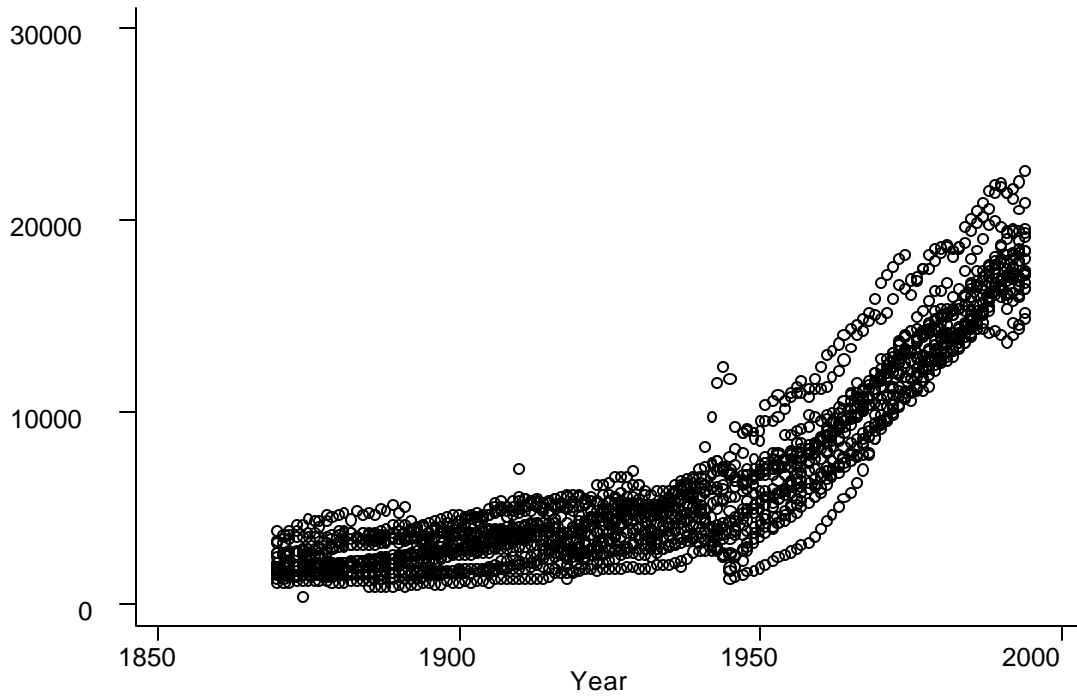**Figure 4: Income Per Capita, 1990 G-K $, Scatter Plot**

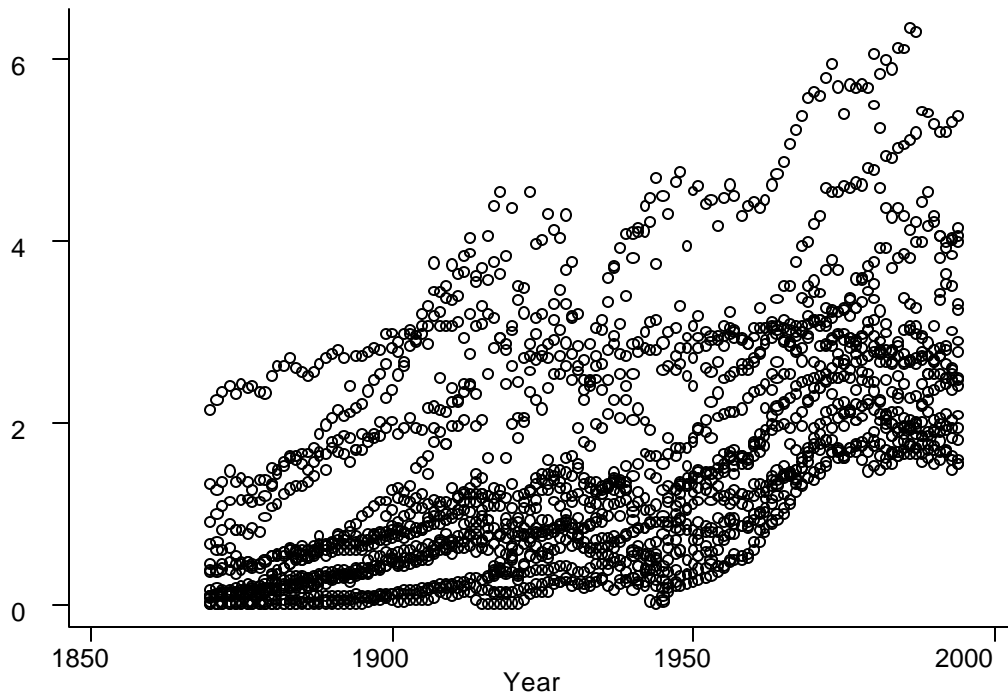**Figure 5: Emissions Per Capita Scatter Plot (metric tons of carbon per 1000)**

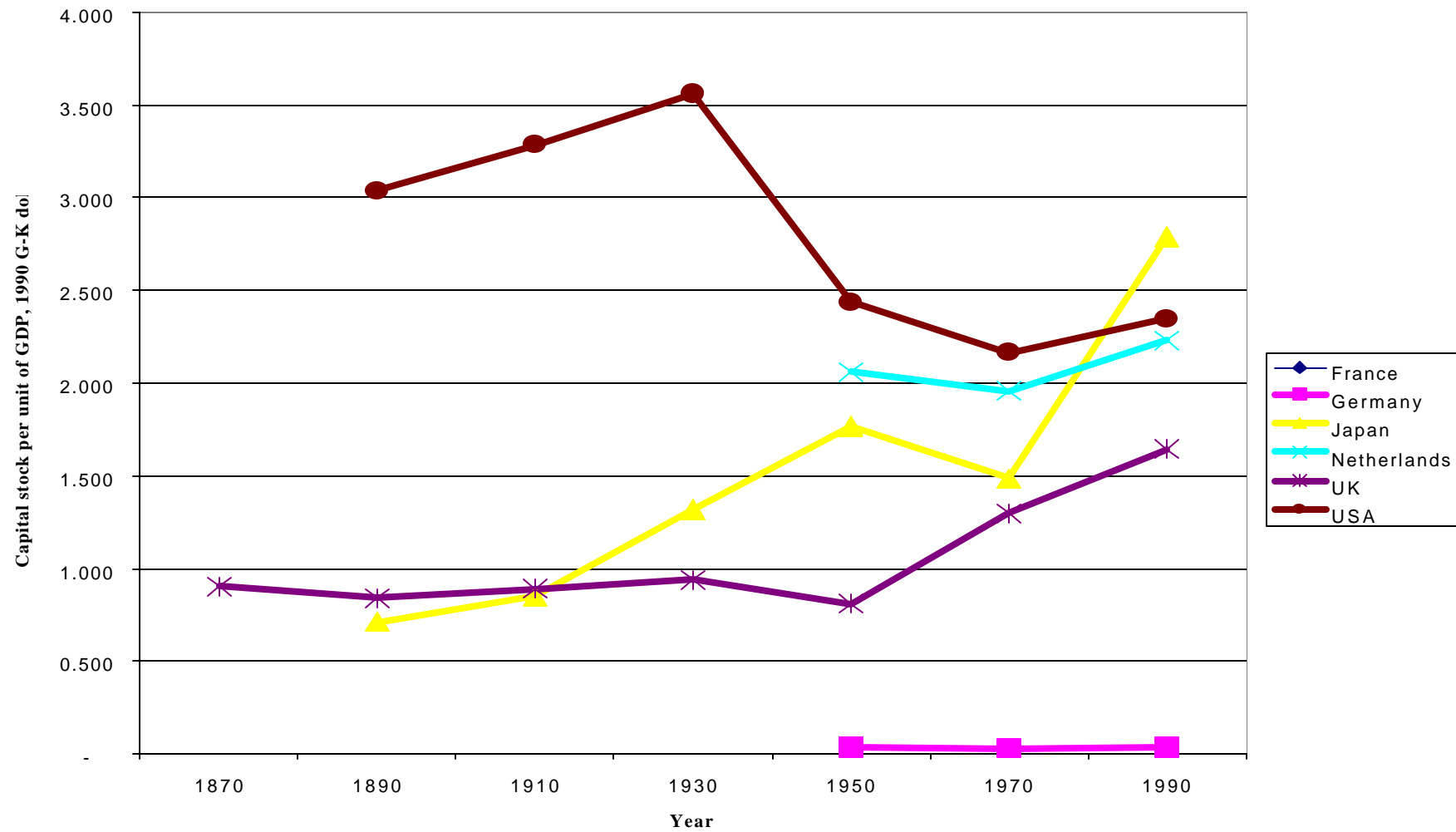**Figure 6: Gross Nonresidential Capital Stock Per Unit of GDP for 6 Industrialized Countries, 1870-1990 (1990 G-K Dollars)**

Figure 7 United Kingdom: Capital Accumulation Per Capita, 1870-1990 (1990 Geary-Khamis dollars)
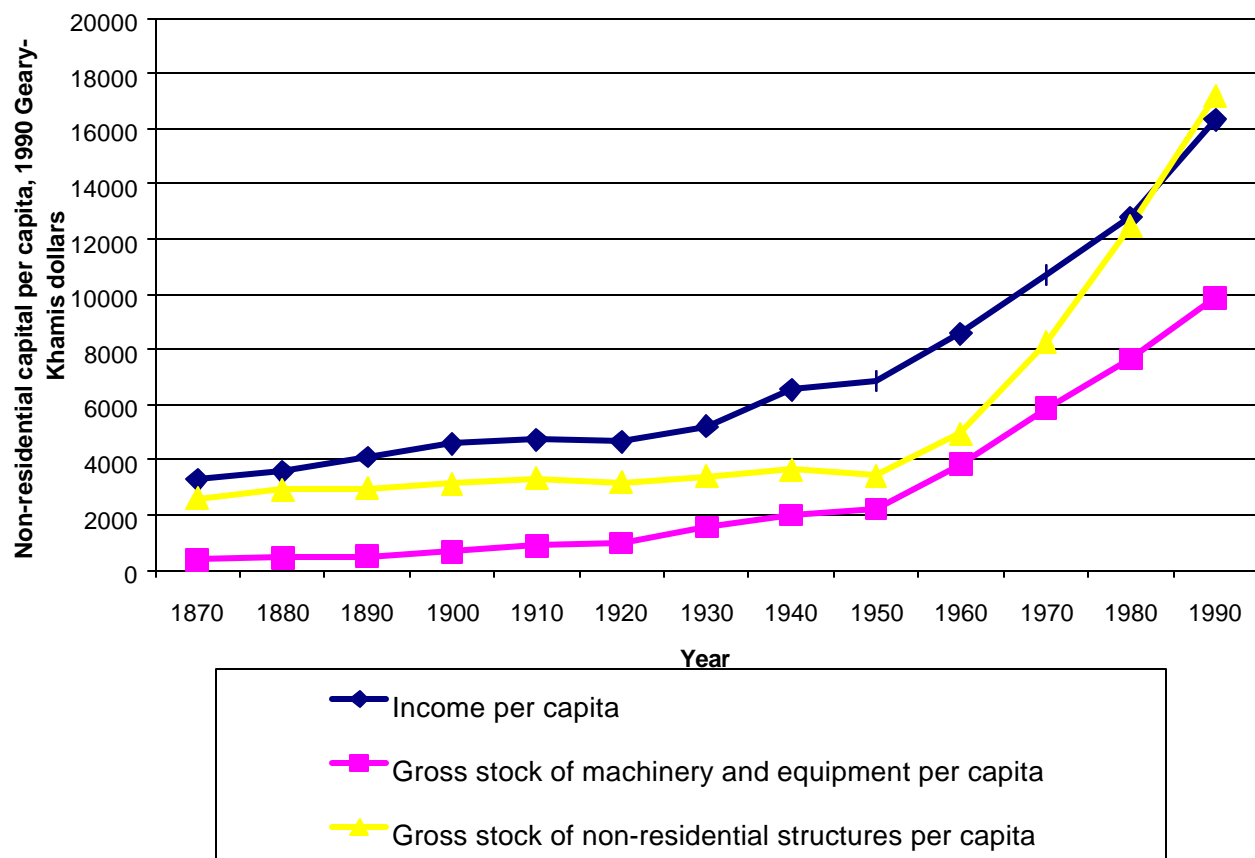
Figure 8: United States: Capital Accumulation Per Capita, 1870-1990 (1990 Geary-Khamis Dollars)
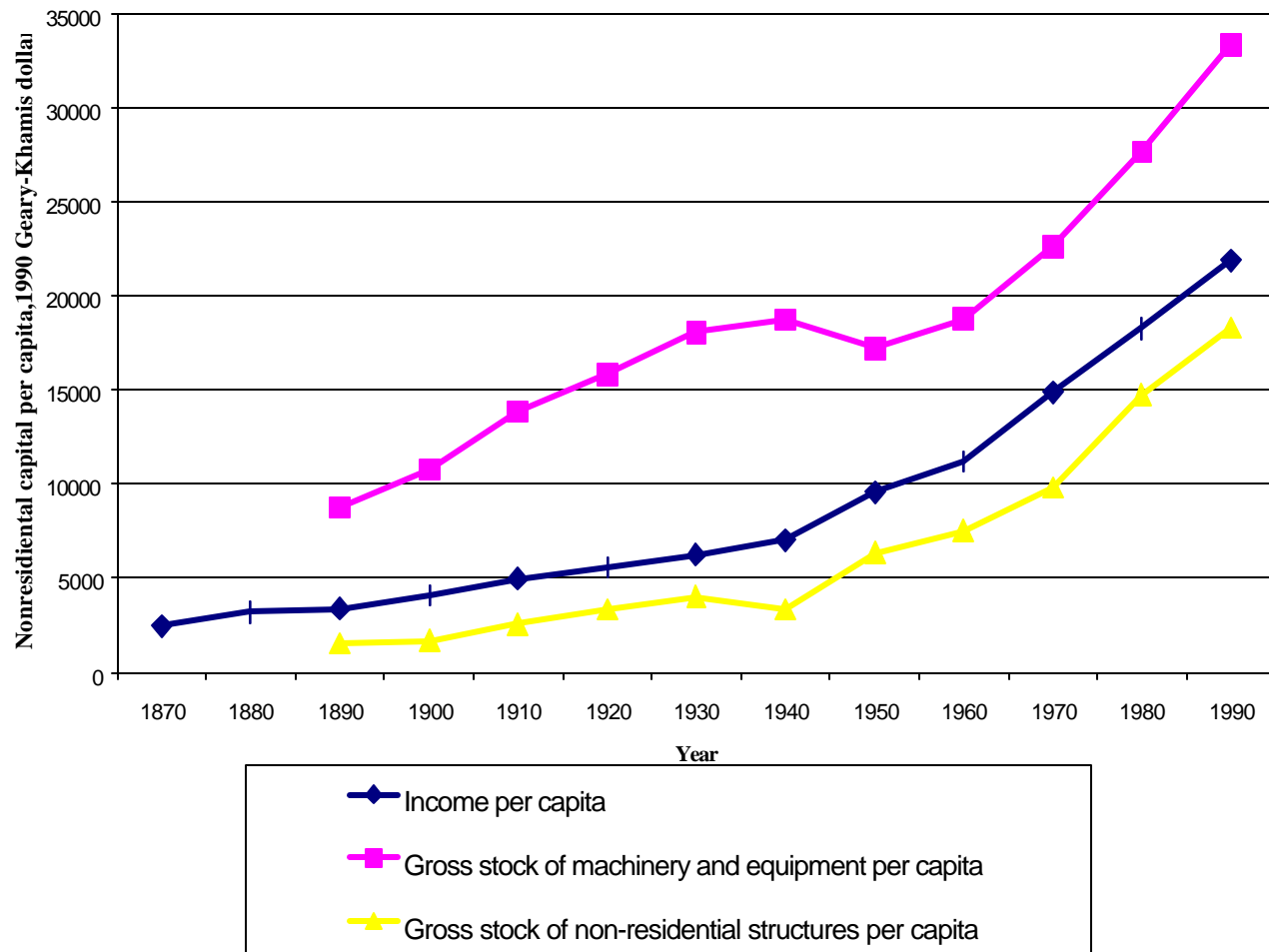
Figure 9: Income Elasticity Panel Regression 1
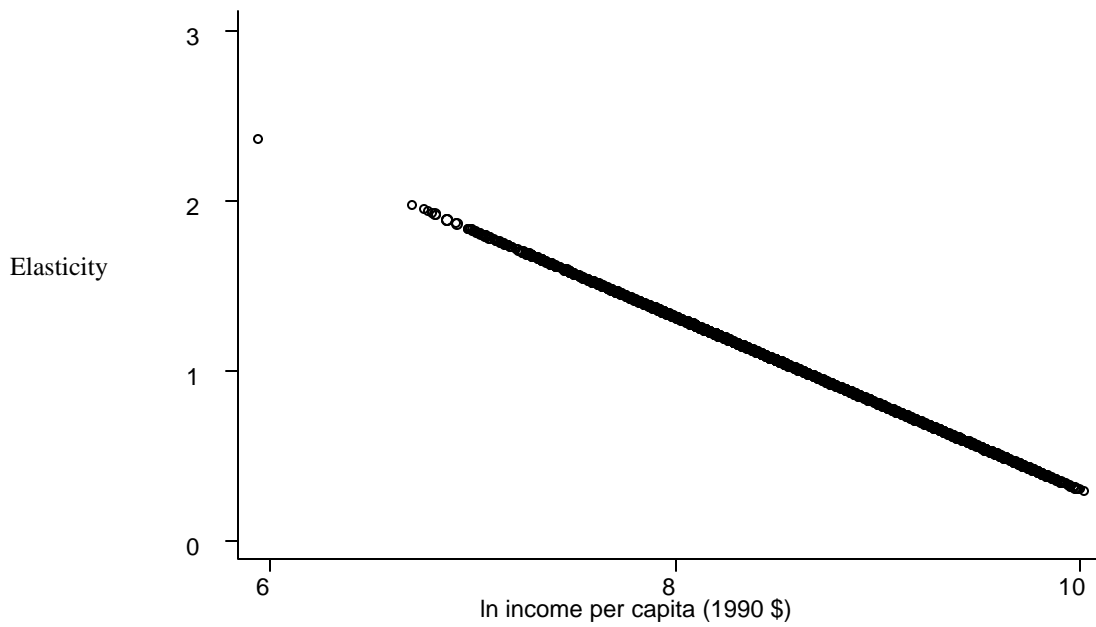
Figure 10: Income Elasticity Panel Regression 2
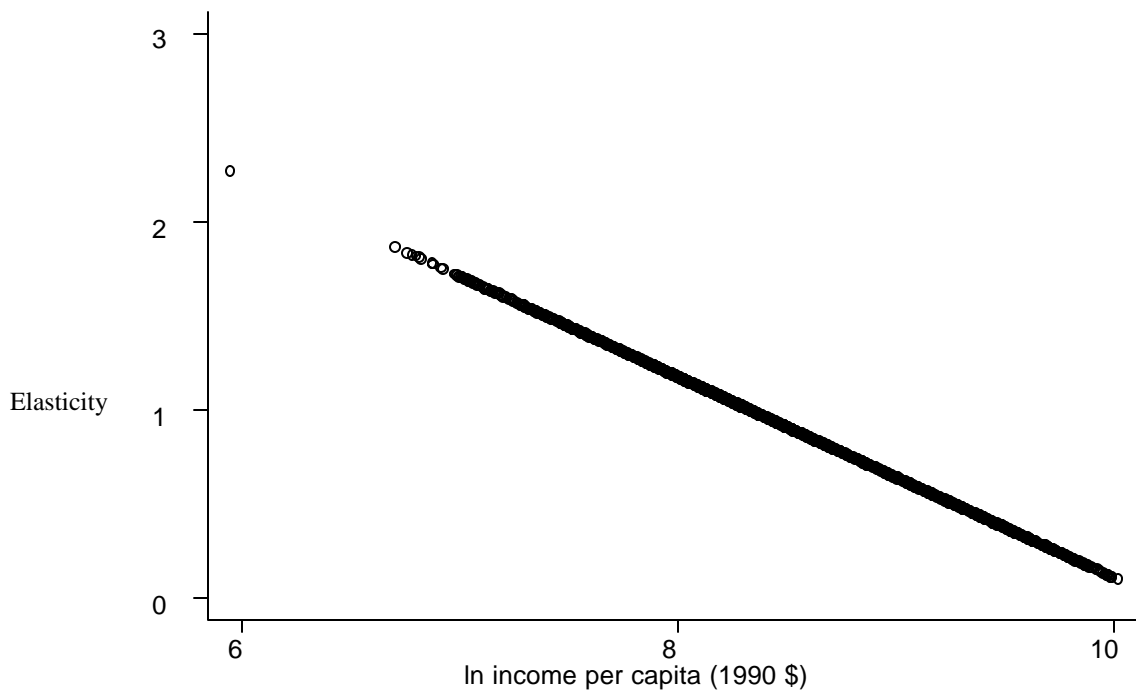
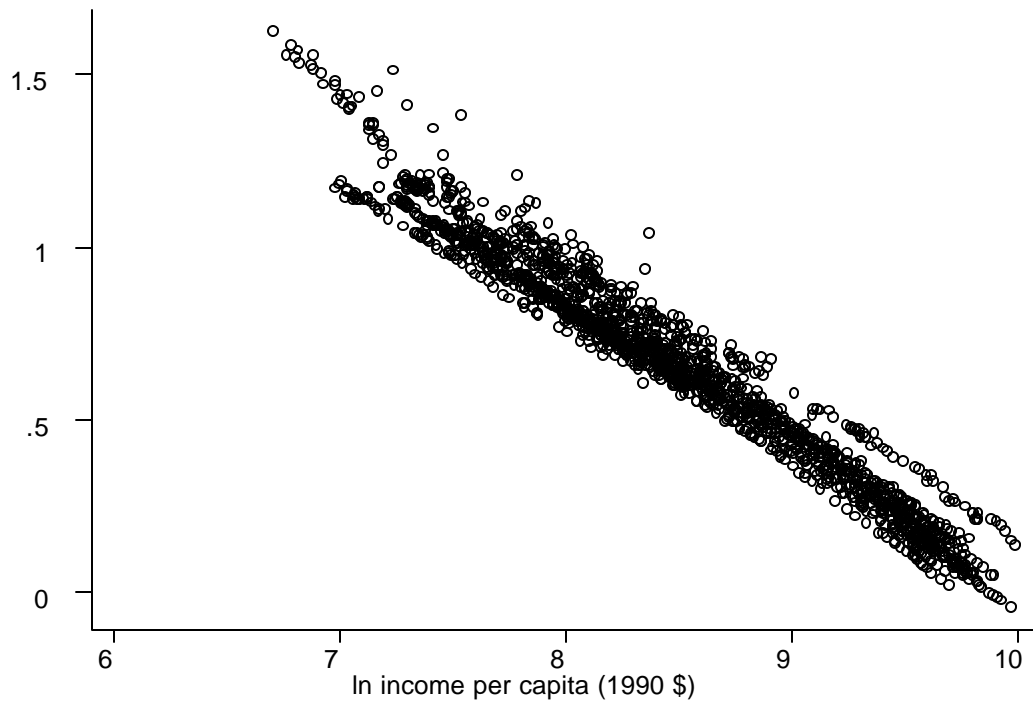**Figure 11: Income Elasticity Panel Regression 5**

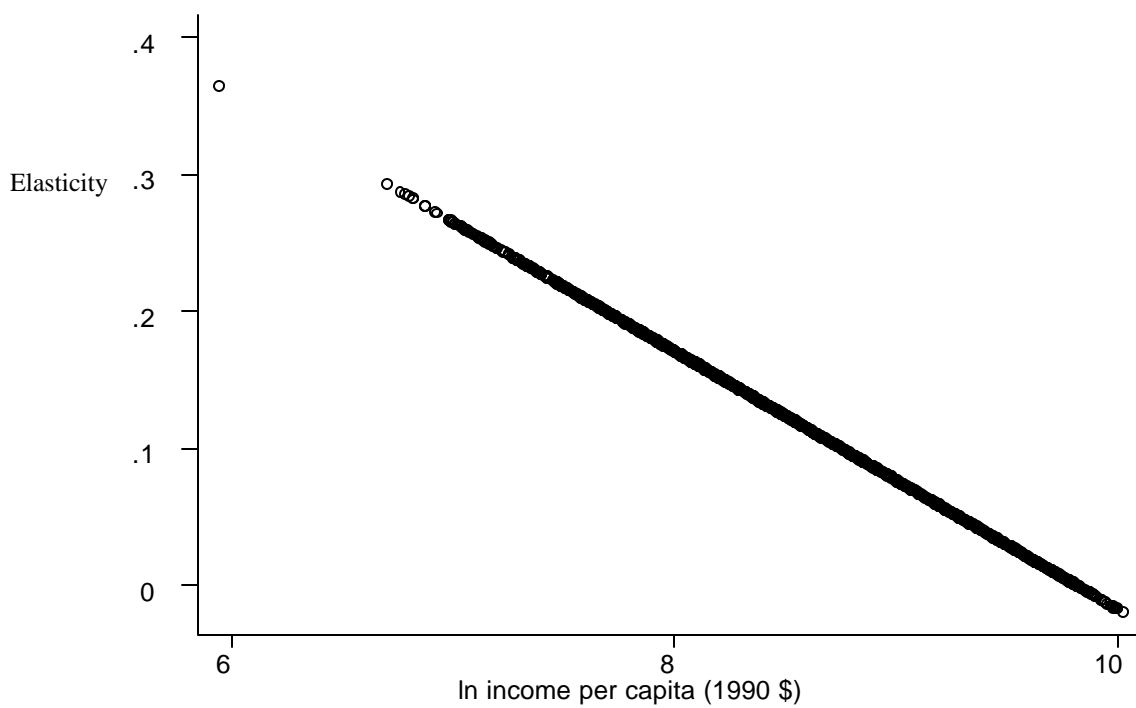

Figure 12: Trade Elasticity Panel Regression 5
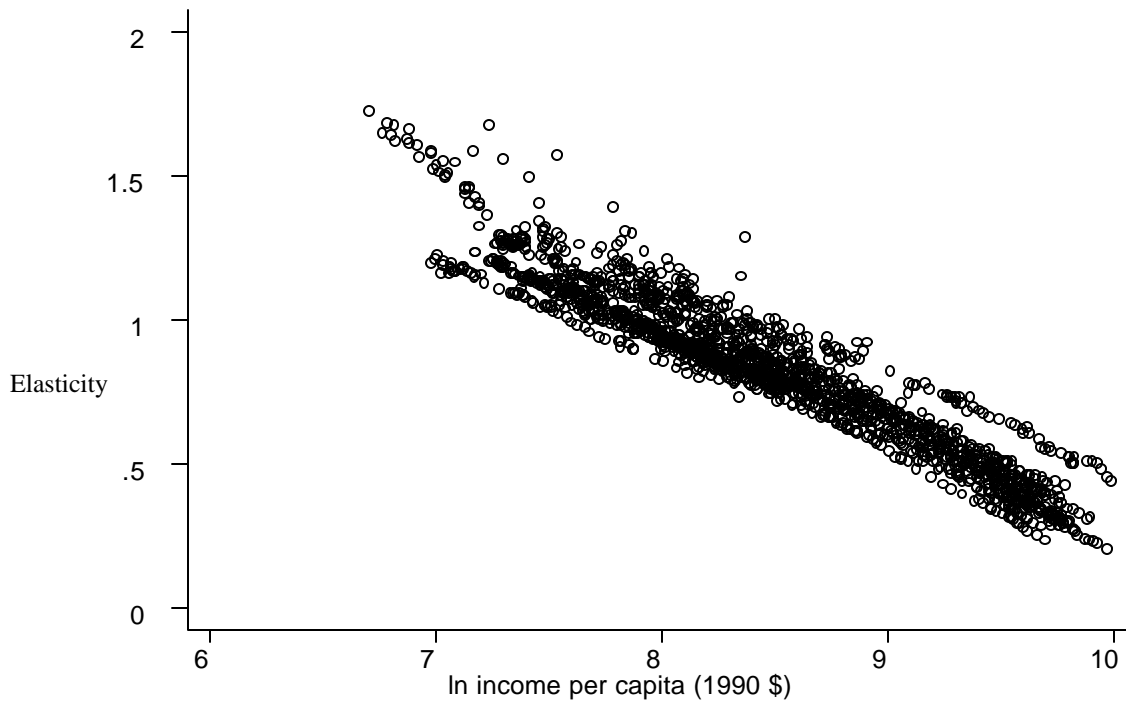
Figure 13: Income Elasticity Panel Regression 8

Figure 14: Trade Elasticity Panel Regression 8